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Impact-induced deformation mechanisms in unstrengthened and chemically strengthened glass bars

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ABSTRACT

Ball impact experiments were performed on unstrengthened and chemically strengthened glass bars at impact velocities of 52–345 m/s. The damage characteristics were captured by high-speed imaging (up to 500,000 frames per second). It was found that the damage front propagation velocity, ejecta velocity, and radial bar dilation depth and velocity increased with increasing impact velocity (i.e., energy). Impact damage in the unstrengthened glass was constrained within a short distance from the impact-end, but the reflected tensile wave caused additional damage at the rear-end of the bar. In contrast, self-sustained damage propagation occurred along the entire length of the strengthened glass bar, which has been attributed to the stored tensile strain energy. Both glasses exhibited similar radial dilation over a finite length from the impact-end; however, an additional mode of uniform dilation over the entire bar length was observed in the strengthened glass. This behavior has been associated with stored energy release from the near-surface regions containing high residual compression. The increased fragmentation and uniform dilation in the strengthened glass bar is proposed to contribute to increased ejecta velocities and greater frictional contact between the ball (impactor) and the glass (target). It was determined that bar dilation, ejecta, frictional contact, and elastic wave propagation encompassed greater than 95% of the total energy dissipated.

1. Introduction

Strengthened glasses have a wide variety of potential civilian and military uses such as screen covers for electronics (e.g., cell phones), hurricane- and earthquake-resistant architectural windows, and even laminate windows for armored vehicles [1]. For dynamic applications where impacts by projectiles, particles, or debris are expected, it is vital to fully understand the influence of processing (residual stress state) on the resultant mechanical response. Additionally, because material behavior at high strain rates can differ drastically from its quasi-static response, experimental observation and characterization of the operative mechanisms of deformation and energy dissipation specific to the high-rate regime must be identified and understood.

Studies performed on glasses and ceramics to determine material properties that can serve as performance metrics often do not indicate a direct link between properties and impact performance [2]. Edge-on impact experiments on plates or rods coupled with high-speed photography have been identified as a suitable means of exploring the impact response and damage mechanisms of transparent materials [3–6]. However, limited experiments have been performed on the impact response of strengthened glasses [6–9]. The focus of the current manuscript is an in-depth examination of the influence of chemical strengthening on the deformation mechanisms for a range of impact velocities. Additionally, the fractional energy absorbed by various deformation modes was estimated by means of an overall energy balance to determine key energy dissipations modes and apparent differences between the unstrengthened and strengthened glasses.

2. Experimental

Unstrengthened and chemically strengthened glass bars of 100 mm (length) × 7.6 mm (depth) × 8.6, 10, or 12 mm (height) were obtained from Saxon Glass Technologies, Alfred, NY, USA. The glass in its "unstrengthened" form was a lithium aluminosilicate glass procured from Nippon Electric Glass, Tokyo, Japan. The unstrengthened glass bars were chemically strengthened by Saxon Glass Technologies using a patented ion exchange process and the resulting glass was trade-named Ion-Armor®. The unstrengthened bars were placed into a bath of mixed molten salts ($NaNO_3$–KNO_3)

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for up to 24 h. During this time, exchanges occurred between the lithium (Li^+) ions in the parent glass and the sodium (Na^+) and potassium (K^+) ions in the salt bath. As the glass substrate cooled, the larger salt ions became "wedged" into the spots once filled by the smaller glass ions. Thus, in the exchanged outer layers of the glass a residual state of compression was developed with a balancing interior residual tension. The exchange process resulted in a thick near-surface compressive layer consisting of two sub layers: a thin (~25 micron) outer layer of ultra-high residual compressive stress up to approximately 1 GPa and a thick inner layer (0.8–0.9 mm) of moderate residual compressive stress up to ~250 MPa [6,10,11]. In the interior of the bar, tensile stresses ranging from 22 to 47 MPa were developed to satisfy equilibrium conditions. For a 12 mm × 7.7 mm × 100 mm strengthened bar, the residual stresses developed within the strengthened glass bars translated to a total stored elastic strain energy density of 8.5×10^4 J/m^3 (8.0×10^4 J/m^3 due to residual compressive stress and 0.5×10^4 J/m^3 due to residual tensile stress) [6]. This corresponded to approximately 0.74 J of residual compressive strain energy and 0.04 J of residual tensile strain energy, based on the volume of the glass bar in a state of residual compression and tension, respectively. The implications of this residual stress and stored strain energy (U_{SE}) on the observed damage mechanisms will be discussed in Section 4.

Ball impact experiments were conducted at a range of impact velocities from 52 to 345 m/s on unstrengthened and strengthened glass bars. The experimental method is a modified version of the Edge-On Impact (EOI) technique developed by the Ernst–Mach–Institut (EMI) [3]. In the current study, normal impact occurs on the edge face of a long rectangular glass bar which allows damage front propagation along its length. The long dimension in the impact direction allows for separation of the impact-damage from the damage developed due to stress wave reflections at the rear-end. The experimental setup, shown in Fig. 1, illustrates a freely supported glass bar impacted by a steel spherical impactor of diameter 4.76 mm and weight 0.44 mg. By freely supporting the bars, the rigid body motion of the target material can also be captured and accounted for rather than the energy being dissipated into the rigid supports. The damage characteristics were captured using a high-speed camera (Vision Research® Phantom v710®) at frame rates up to 500,000 frames per second (fps) with minimum interframe time of 2.0 μs. Two different optical configurations were used: reflected light and transmitted light. The reflected light arrangement exploited light reflections from the developing cracks and damaged regions to observe the fracture development and damage make-up. Transmitted light relied on the disruption of the light transmission by damage formation and provided improved contrast between damaged and intact glass regions.

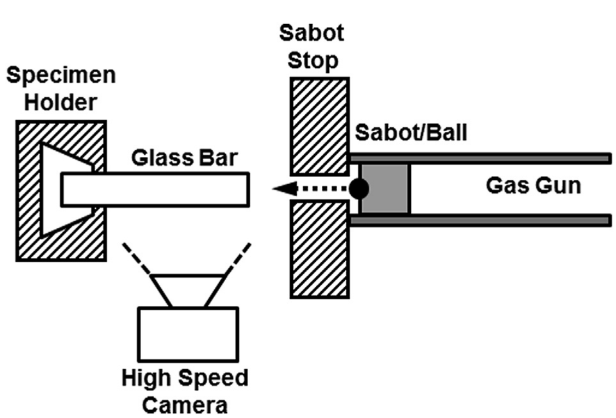

Fig. 1. Schematic of the test setup used for ball impact experiments.

Selected material properties of relevance in this study for the unstrengthened glass, strengthened glass, and the steel projectiles are provided in Table 1. Clearly, the strengthening process can result in an increase in the strengthened glass properties compared to the unstrengthened glass, most notably the fracture strength which can generally be considered as the level of residual compression that must be overcome to cause failure [12]. These properties were used to better understand the impact-induced damage evolution and to calculate discrete values for the observed energy dissipation modes, as discussed in Section 3.2.

3. Results and discussion

3.1. Impact damage evolution

The damage developed in the unstrengthened and strengthened glass bars was analyzed from the high-speed images, shown in Figs. 2 and 3. The operative damage mechanisms were found to be highly dependent on the impact velocity and the available energy to activate the damage. Thus, two impact velocity regimes were classified as low velocity impact (~50–60 m/s) and moderate velocity impact (~150–350 m/s). For reference, note that the impact generates a longitudinal compressive wave, a transverse shear wave, and a Rayleigh surface wave in the glass bar, whose elastic wave velocities for the unstrengthened and strengthened conditions are given in Table 1.

3.1.1. Low velocity impact

For a low velocity impact (52 m/s) on the unstrengthened glass bar, fracture surface creation was the only observable inelastic deformation mechanism (see Fig. 2(a)). The damage propagation velocity quickly reached a maximum velocity of 1627 m/s (see Fig. 4(a)), and arrested rapidly within 10 μs and at a distance of 11 mm from the impact-end. Also, it was observed that a well-defined cone crack was formed during the early stage of damage development. The ball was then observed to penetrate slowly into the bar with a residual velocity of ~16 m/s (~31% of the initial velocity). Here, once structural cohesion was lost the large macroscopic fragments were simply pushed out of the way, allowing the ball to slowly penetrate the debris.

In contrast, for a 62 m/s impact on the strengthened glass, no well-defined cone-crack was observed, perhaps due to an increased level of fragmentation fueled by the additional stored elastic energy (residual stresses) (see Fig. 2(b)). However, cone-shaped damage was observed to partially extend from the impact plane during the early stage of damage development. Instead of large cracks, a highly

Table 1
Selected material properties for the unstrengthened glass, the strengthened glass, and the steel ball.

Property	Unstrengthened glass	Strengthened glass	Steel ball
Density (g/cc), ρ	2.41 [6]	2.46 [6]	7.87 [4]
Elastic Modulus (GPa), E	81.4 [6]	85.0 [6]	213.0 [4]
Shear Modulus (GPa), G	33.3 [6]	35.0 [6]	80.0 [13]
Poisson's Ratio, ν	0.22 [6]	0.21 [6]	0.30 [4]
Vickers hardness (GPa), H	6.0[a] [10]	6.5[a] [10]	5.9 [13]
Fracture strength (MPa), σ_F	14–70 [12]	>1000 [6,10,11]	2150 [13]
Longitudinal wave velocity (km/s), C_L	6.13 [6]	6.23 [6]	5.20[b]
Shear wave velocity (km/s), C_S	3.69 [6]	3.79 [6]	3.19[b]
Rayleigh wave velocity (km/s), C_R	3.36 [6]	3.44 [6]	2.95[b]

[a] Dynamic Vickers hardness values.
[b] Computed using Eqns. (A.1)–(A.3) in Appendix A [35].